GaN-based Robust Micro Pressure and Temperature Sensors for Extreme Planetary Environments

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Abstract— We are developing robust GaN-based microsensors for simultaneous temperature and pressure measurements in extreme planetary atmosphere. Among the various AlGaN/GaN heterostructure devices, n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) vertical transport devices are investigated in this work. Our research performed for n-I-n sensors fabricated with various compositions (x = 0.1, 0.15, & 0.3) of $Al_xGa_{1-x}N$ suggests that electrical currents decrease linearly and reversibly with increased pressure within the range that we measured (0-500 MPa), and this effect becomes more significant with higher AlN compositions in the $Al_xGa_{1-x}N$ layer. The linearity and reversibility in pressure response observed with n-I-n devices suggest that they are promising for pressure sensor applications in extreme environments. Temperature effects on electrical properties of the GaN-based sensors have also been measured, and detailed analysis on the results is in progress.

I. INTRODUCTION

GaN (Gallium nitride) and $Al_xGa_{1-x}N$ (Aluminum gallium nitride) have large band gaps (3.4 - 6.0 eV at room temperature) and strong atomic bonds. Consequently, these semiconductors exhibit favorable mechanical properties and excellent thermal and chemical stabilities. They are hardy against radiation and have minimal problems associated with the unwanted optical or thermal generation of charge carriers [1-4]. Therefore $Al_xGa_{1-x}N$/GaN-based sensors are strong candidate for extreme and harsh environment applications. One of the unique advantages of GaN-based devices is that AlGaN/GaN heterostructures develop sheet charges at the hetero-interfaces due to spontaneous and piezoelectric polarizations [5-8]. Applied stress modulates this interfacial polarization charge due to differences in the piezoelectric coefficients of AlGaN and GaN, and therefore the barrier height (that controls transport across the interface) is modulated [2,3,9-12]. In this work, n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) vertical transport devices are investigated to measure their pressure responses. The n-I-n device has been selected for study due to the high sensitivity of barrier height to stress and the high stability of device operation expected at increased temperatures. While higher pressure sensitivity will be achieved with the devices fabricated on a membrane or on free-standing GaN [11,13], we investigated the devices fabricated on a standard sapphire substrate with the objective of determining the most promising AlGaN/GaN heterostructure for pressure sensing. Electrical properties of the GaN sensors have also been measured as a function of temperature to asses their potential as temperature sensors.

II. EXPERIMENTAL

Single barrier heterostructures of n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) with various Al content and thickness of $Al_xGa_{1-x}N$ thickness have been studied to measure pressure responses in this work (Table 1). The n-I-n structures were grown on sapphire substrates by organometallic vapor phase epitaxy (OMVPE) using epitaxial lateral overgrowth (ELO). The details of growth procedures and the layer structure are described in reference 14.

A schematic of the n-I-n structure is shown in figure 1 and an optical microscope image is shown in figure 2. Circular shape n-I-n mesa structures 250 μm diameter are created with BCl_3 reactive ion etching. Ohmic contacts are made with a stack of Ti/Al/Ti/Au layers deposited with e-beam evaporation. The contacts (200 μm diameter) are formed on the highly doped (N_d~3x $10^{18}/cm^3$) top and the

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bottom n-GaN layers by rapid thermal annealing in a nitrogen environment. During the measurements of vertical current transfer, the bottom contact is set at ground and a bias voltage is applied to the top contact.

Pressure response of the n-I-n devices is measured in a liquid pressure cell from the Polish Academy of Sciences, where hydrostatic pressure is applied to the devices through a liquid medium (i.e., 1:1 mixture of n-hexane and n-pentene) while measuring current of the devices via built-in electrical feedthroughs [15-16]. Vertical transport current of the devices is measured at a constant bias voltage with both increasing and decreasing pressures. Hydrostatic pressure in the pressure cell was measured using an InSb pressure gauge.

TABLE I. The n-I-n sensors investigated for pressure responses. AlGaN layer composition, thickness, maximum pressure gauge factor (PGF), and maximum strain gauge factor (SGF) are shown for the samples tested under hydrostatic pressure.

Sample Parameters		Maximum	Maximum
x	t_{AlGaN} [nm]	PGF [GPa^{-1}]	SGF
0.12	20	-0.492	386
0.15	20	-0.541	425
0.30	20	-1.02	807
0.15	10	-0.626	492
0.15	30	-0.3	236

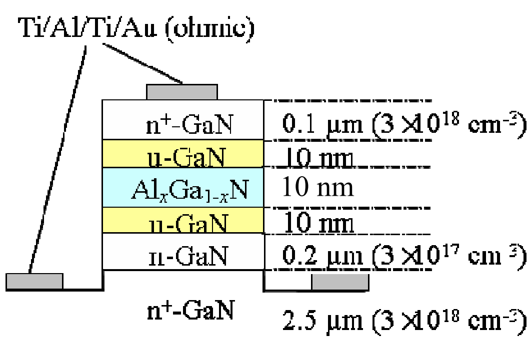

Figure 1. Schematic of the n-GaN/$Al_xGa_{1-x}N_x$/n-GaN (nIn) devices investigated.

III. RESULTS & DISCUSSION

Our theoretical modeling of the n-I-n devices indicate that the current will decrease with increasing pressure, and the amount of current change due to the applied pressure increases as the AlN compositions and $Al_xGa_{1-x}N$ thickness increase within the ranges examined. Applied pressure modulates the polarization charge density at the AlGaN/GaN interfaces resulting in an increased barrier height and thus reduced current [17].

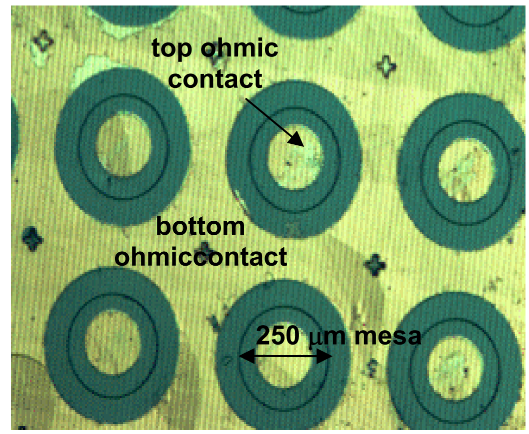

Figure 2. Optical image of n-GaN/Al0.15Ga0.85N /n-GaN heterojunction devices used for pressure measurements. The heterostructure was grown on a sapphire surface using OMVPE. The Al0.15Ga0.85N layer was undoped and 20 nm thick. The diameter of the heterojunction mesa structure is 250 µm.

The effects of hydrostatic pressure on the electrical characteristics of the n-I-n devices are also probed experimentally. Figure 3 shows the results taken for the n-I-n device fabricated with a 20 nm thick $Al_{0.15}Ga_{0.85}N$ layer.

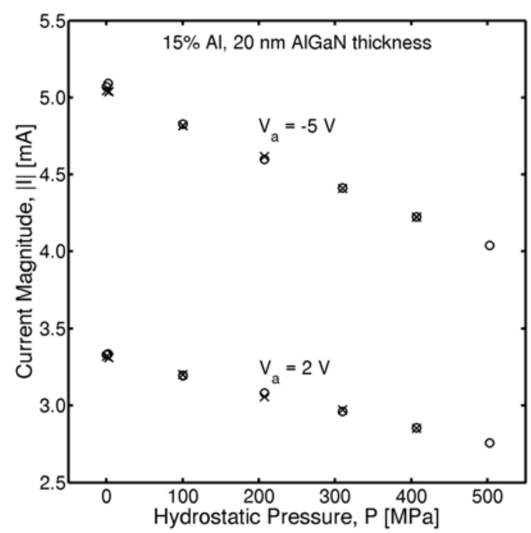

Figure 3. Pressure response measured for the n-GaN/$Al_{0.15}Ga_{0.85}N$ /n-GaN single barrier vertical transport device. Current was measured under hydrostatic pressure at a fixed forward bias (-5 V & +2 V) with increasing (open circle) and decreasing (cross) pressure. Linear decrease of the current with increasing pressure was observed and the response was reversible.

As predicted by theoretical modeling, the current decreases with increasing pressure. In the data shown, the current was measured with 2 V and -5 V forward biases at room temperature while cycling the pressure between 0 and 500 MPa. The open circles correspond to the measurements made with increasing pressure while the crosses are for the data taken with decreasing pressure. The change in the current is ~ 20 % over a 500 MPa range in pressure (Fig. 5), resulting in a sensitivity of 2 μA/MPa. This sensitivity is mainly limited by the rigidity of the thick sapphire substrate and can be increased significantly if the device is fabricated on a membrane or on a free-standing GaN template [11,13]. One very important fact to note is that the n-I-n response to applied pressure is highly linear and reversible over the pressure range examined, which is crucial for pressure sensing applications.

In order to compare pressure responses of the various n-I-n devices investigated, a "pressure gauge factor (PGF)" is calculated. Here the PGF is defined as a normalized current change per unit pressure:

$$PGF = \frac{I(P) - I(0)}{I(0)} \cdot \frac{1}{P}.$$

where I(0) is the current taken at zero applied pressure, I(P) is the current under hydrostatic pressure, and P is the applied pressure. In Figure 4, the PGF (open circles) is plotted as a function of applied voltage for the n-I-n device with 20 nm-thick $Al_{0.15}Ga_{0.85}N$. A significant variation of the PGF is observed over the range of applied voltages with a maximum near the turn-on voltage in both directions. The maximum PGF obtained for this device is -0.541 GPa^{-1}. A similar trend has been observed with the other n-I-n devices tested. Values near zero bias are affected by noise due to the small current magnitudes. At large applied voltages, the series resistance tends to reduce the sensitivity of the device as a pressure sensor.

While the PGF is useful for indicating the relative change in current per unit pressure, denoting the performance using a strain-based metric rather than pressure-based is also useful. Since the pressure response of these devices is dominated by the substrate material, we can convert the PGF to a strain gauge factor (SGF) by dividing the PGF by the induced in-plane elastic strain per unit of applied pressure. Based on the elastic constants for sapphire [18], a pressure-induced in-plane strain of -1.273×10^{-3} GPa^{-1} is calculated for sapphire. This leads to a maximum SGF of 425 for the data presented in Figure 4. In table 1, pressure and strain gauge factors of all the n-I-n devices investigated are listed. Higher PGF and SGF are observed for the n-I-n sensors fabricated with higher Al content in the $Al_xGa_{1-x}N$ layer.

Temperature responses of the n-I-n sensor have been measured. Figure 5 shows the current measured as a function of temperature for the 20 nm-thick $Al_{0.15}Ga_{0.85}N$ n-I-n sensor. While this is preliminary data and further measurements and investigation are underway, the good linearity observed between temperature and current looks promising for n-I-n based temperature sensing.

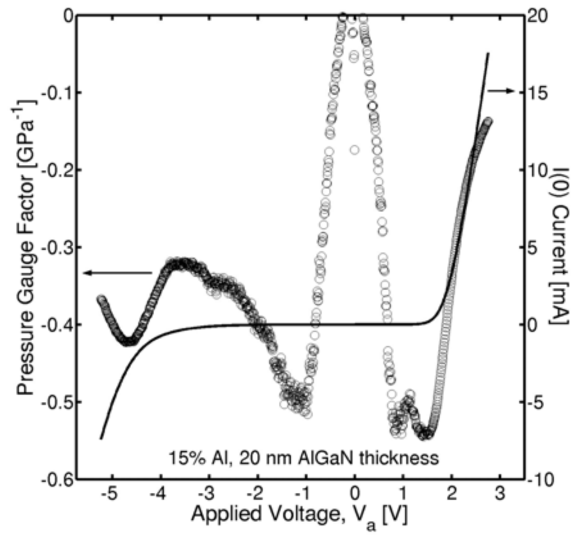

Figure 4. Pressure gauge factor (open circles) obtained over a range of applied voltage for the n-I-n sensor fabricated with 20 nm-thick $Al_{0.15}Ga_{0.85}N$ layer. The zero-pressure I-V curve (solid line), I(0), is superimposed on the plot.

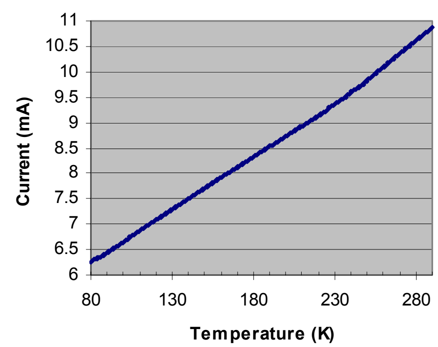

Figure 5. Temperature response of the n-I-n sensor fabricated with 20 nm-thick $Al_{0.15}Ga_{0.85}N$ layer. The current was measured with a forward bias of 1.5 V. Relatively good linearity is observed between current and temperature.

IV. Summary

We have investigated n-GaN/$Al_xGa_{1-x}N$/n-GaN (n-I-n) heterostructural vertical transport devices for potential use as pressure sensors in extreme environments. Based on our modeling results performed previously, vertical transport n-GaN/$Al_xGa_{1-x}N$/n-GaN structures were fabricated with various compositions (x = 0.1, 0.15, & 0.2) and thicknesses (10, 20, 30 nm) of $Al_xGa_{1-x}N$, and vertical transport current was measured over the range of 0-500 MPa at room temperature. The current showed a linear decrease with increasing pressure and the current decrease became more significant with higher AlN compositions in the $Al_xGa_{1-x}N$ layer. The linearity and reversibility observed in pressure response suggest that n-GaN/$Al_xGa_{1-x}N$/n-GaN devices are promising candidates for high-pressure sensor applications in extreme environments.

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